Recent Rare K Decay Results

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Although data taking was some years ago the K decay experiments KTeV and NA48 are still producing many interesting results on rare decays.

We define rare decays in two ways:

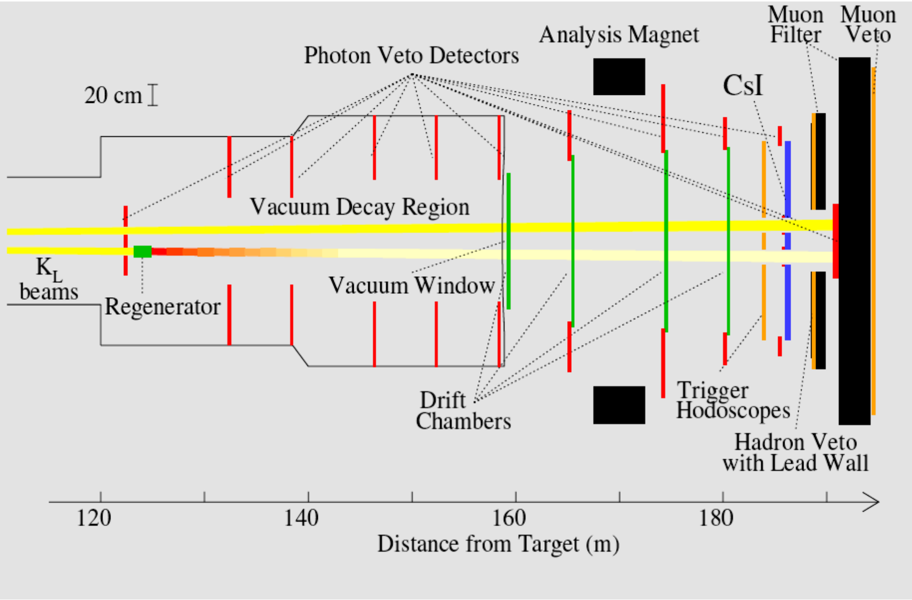
1) Pushing the smallest branching fractions observable to smaller and smaller levels.
2) Obtaining large statistics on previously observed decays to study their properties in more detail.

Results will be presented on the following modes

mode	Approx BR	Number of events
$K_L \rightarrow \pi^+\pi^-\gamma$	1×10^{-5}	112,000
$K^\pm \rightarrow \pi^\pm\pi^0\gamma$	3×10^{-4}	124,000
$K_L \rightarrow \pi^+\pi^-\pi^0\gamma$	2×10^{-4}	5600
$K_L \rightarrow \pi^+\pi^-\pi^0 e^+e^-$	2×10^{-7}	132
$K_L \rightarrow e^+e^-\gamma$	1×10^{-5}	100,000
$K_L \rightarrow \pi^\pm e^\mp \nu e^+e^-$	1×10^{-5}	19,500
$\pi^0 \rightarrow e^+e^-$	7×10^{-8}	794
$K_L \rightarrow \pi^0\pi^0\mu^\pm e^\mp$	$< \text{few} \times 10^{-10}$	?

($K_L \rightarrow \pi^0\gamma\gamma$ $K_L \rightarrow \pi^0 e^+e^-\gamma$ $K_L \rightarrow \pi^0\pi^0\gamma$ in E.Cheu's talk)

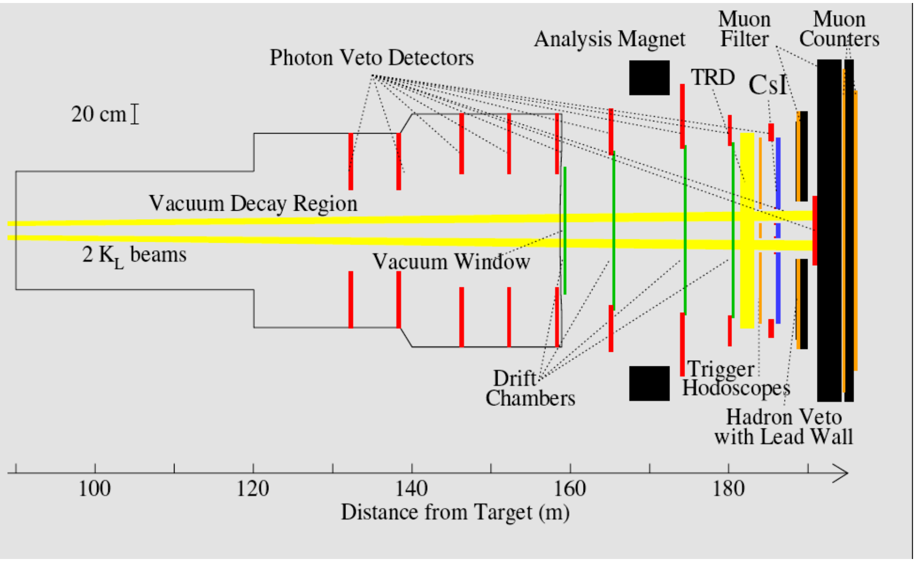
KTeV Configurations



E832 K_L and regenerated K_S

for ε'/ε measurement

Magnet p_t kick 400 MeV/c



E799 2 K_L (vacuum) beams

for rare decays

Magnet p_t kick 200 MeV/c in 1997
And 150 MeV/c in 1999

KTeV used very clean K_L beams generated by 800 GeV/c protons on a BeO target.

Large vacuum decay region surrounded by veto counters

Tracking: Magnet surrounded by 2 sets of 2 x/y drift chambers

3100 element CsI EM calorimeter

$\sigma(E)/E = 0.45\%(+)2\%/\mathrm{sqrt}(E)$

Muon absorber and scintillator hodoscopes

KTeV had two runs 1997 and 1999.

E832 1999 about same sensitivity as 1997 at somewhat lower intensity – to check ε'/ε

E799 1999 lowered magnet kick to increase acceptance (for 4 track modes especially)

some triggers prescaled.

Sensitivity:

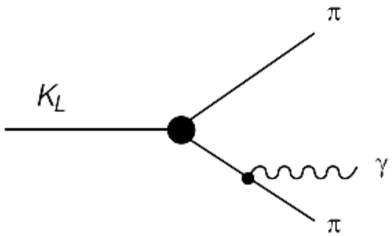
1997 2.5 X 10^{11} K_L decays

1999 3.5 X 10^{11} K_L decays

Radiative Decay $K_L \to \pi^+\pi^-\gamma$

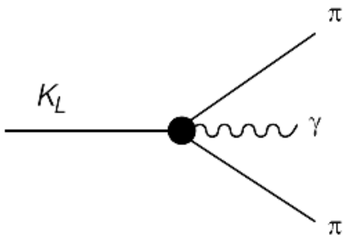
(John Shields and Michael Ronquest, University of Virginia)

internal bremsstrahlung



CP-violating

direct emission



DE coupling requires energy dependence:

$$|g_{M1}| = \tilde{g}_{M1}\left[1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_\gamma}\right]$$

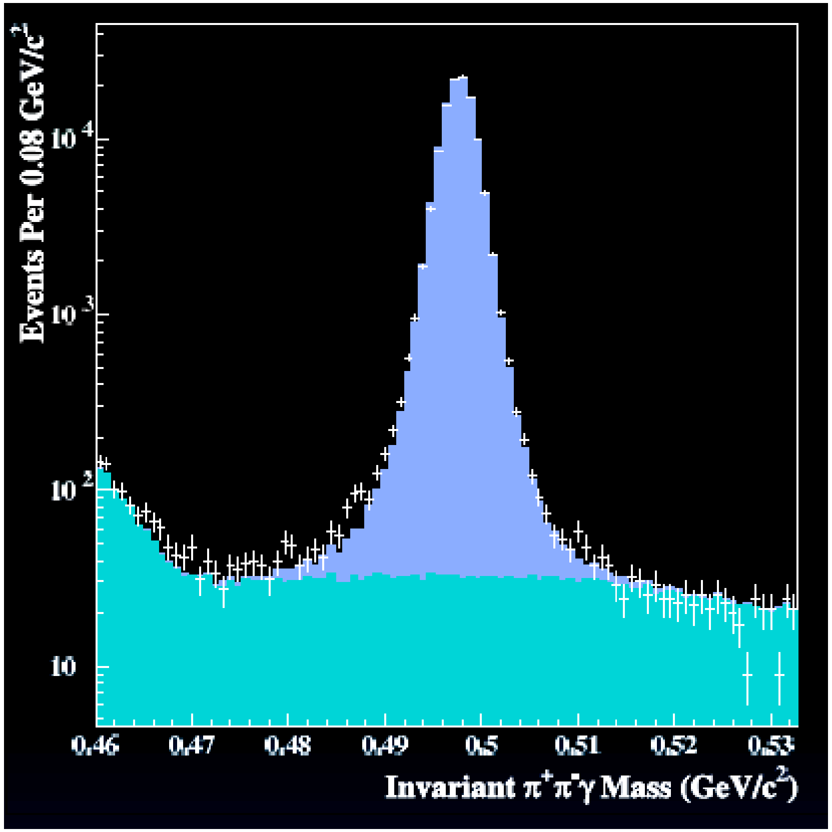
Direct emission can have M1,E1,M2,E2… multipoles

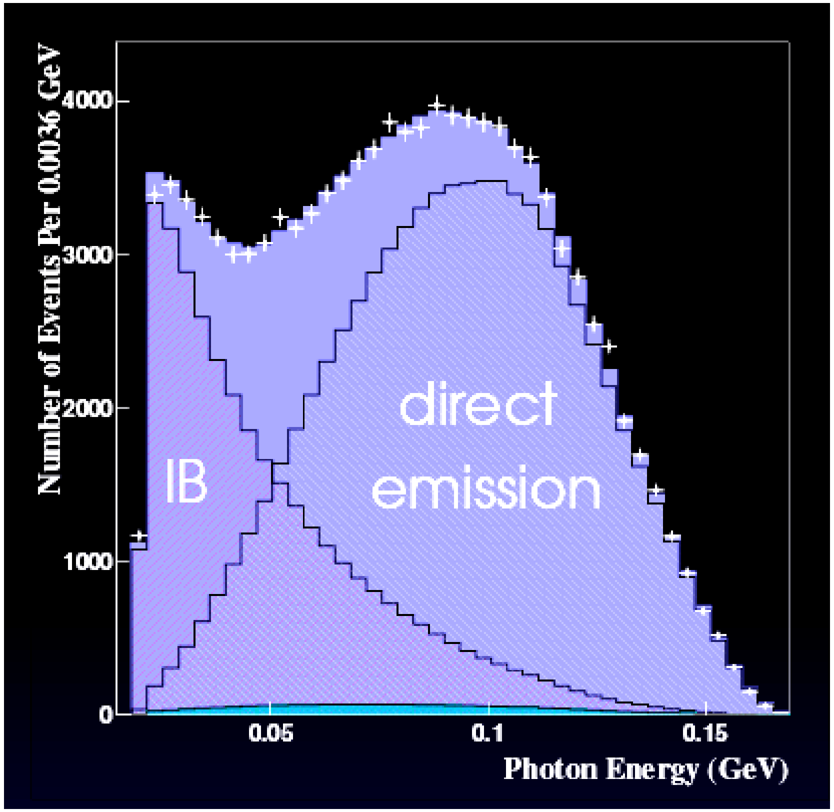
E1 is CP violating.

1997 dataset of E832 (collected during ϵ'/ϵ data taking)

After all analysis cuts: 112.1×10^3 candidates including background of 671 ± 41 events.

Likelihood fit to full-differential decay amplitude.





KTeV Results for $\pi^+\pi^-\gamma$

Form Factor parameters:

$$\frac{a_1}{a_2} = -0.738 \pm 0.007 \pm 0.018 \; (GeV^2)$$

$$\tilde{g}_{M1} = 1.198 \pm 0.035 \pm 0.086$$

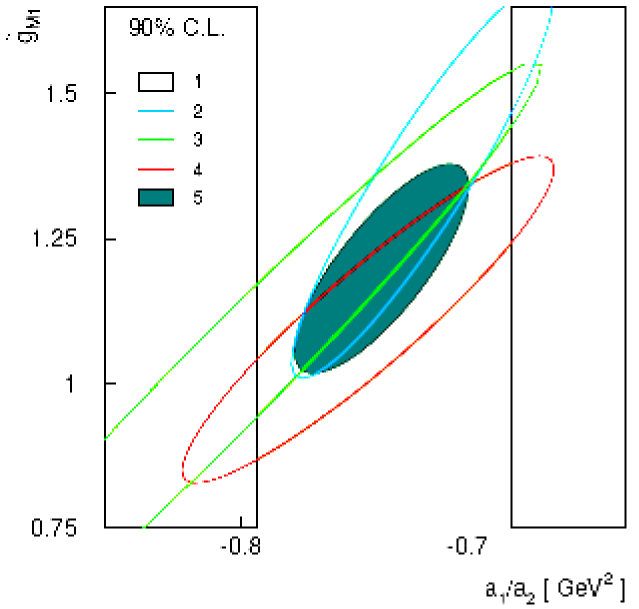
Decay rate for $E_\gamma > 20$ MeV:

$$\frac{DE}{DE + IB} = 0.689 \pm 0.021$$

CP violating E1 DE:

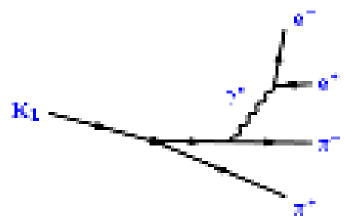
$$|g_{E1}| < 0.21 \; (90\% CL)$$

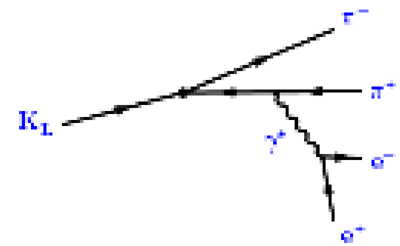
Figure: 90% contours for $\tilde{g}_{M1}$ vs a_1/a_2 for known experimental results:
1 - KTeV($\pi\pi\gamma$). PRL 86,761(2001)
2 - KTeV($\pi\pi ee$). PRL 84,408(2000)
3 - NA48($\pi\pi ee$). EPJ C30,33(2003)
4 - KTeV($\pi\pi ee$). PRL 96,101801(2006)
5 - KTeV($\pi\pi\gamma$). This Result, accepted to PRD



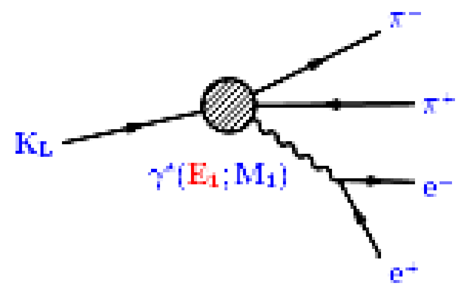
Can also use related decay $K_L \to \pi^+\pi^- e^+e^-$

Has additional charge radius term

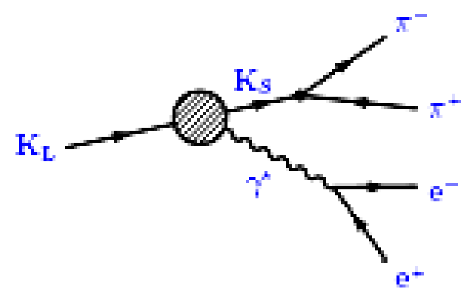




More sensitive to possible E_1 term than is $K_L \to \pi^+\pi^-\gamma$



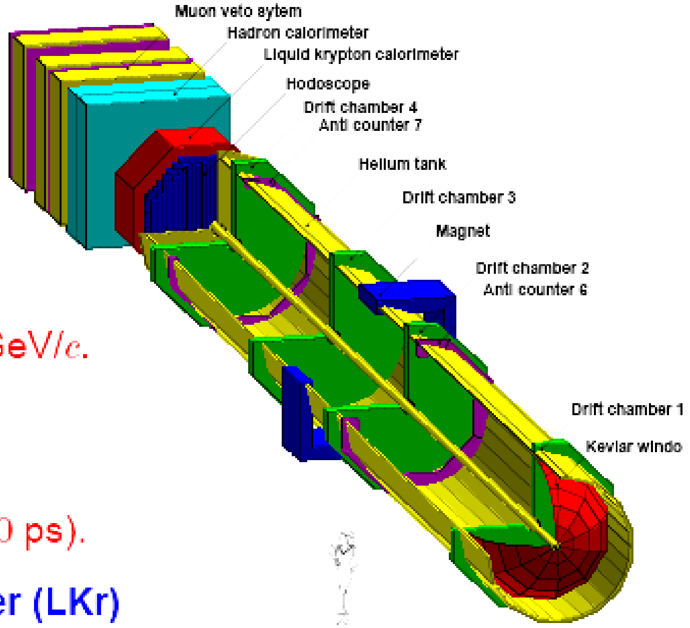
$|g_{E1}|/|g_{M1}| < 0.04$ (90% CL)



NA48/2 results on $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$

(Silvia Goy-Lopez and Mauro Raggi)

The NA48 Detector



Detector components:

- **Magnet spectrometer**

  4 sets of drift chambers.

  $\Delta p/p \approx 0.5\%$ for $p = 20$ GeV/c.

- **Hodoscopes:**

  Fast trigger, precise time measurement ($\sigma_t = 150$ ps).

- **Liquid Krypton Calorimeter (LKr)**

  $\Delta E/E \approx 1.0\%$ for $E_{e,\gamma} = 20$ GeV/c.

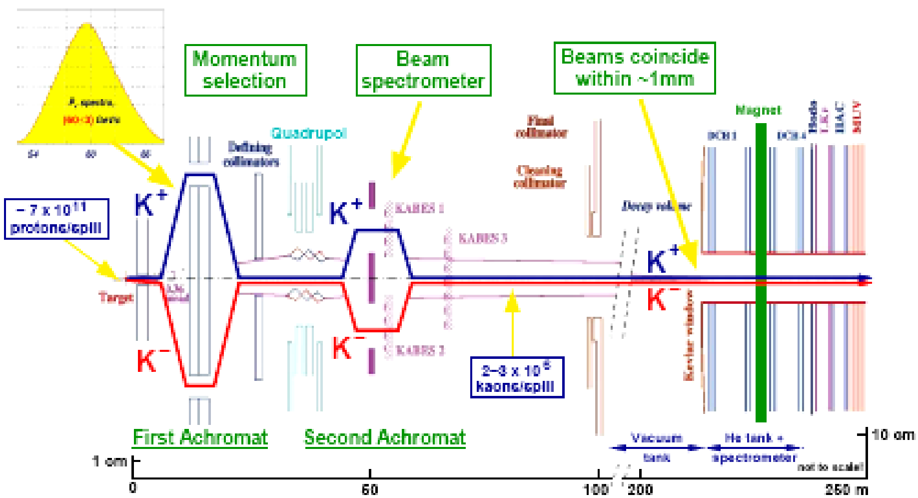
- **Hadron calorimeter, photon vetos, muon counters**

Rainer Wanke, Universität Mainz, ICHEP 2006, Moscow, July 29, 2006 – p.3/16

$K^{\pm}$ Decays: The NA48/2 Experiment

Data taking in 2003/2004: *(NA48/2 experiment)*

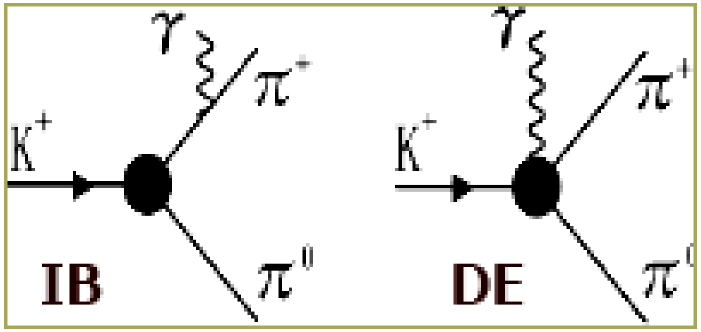
- **Main aim:** Search for direct CP violation in $K^{\pm} \to 3\pi$ decays.
- Simultaneous K^{+} and K^{-}**beams**, with $p_{K^{\pm}} = (60 \pm 3)$ GeV/c.
- **Total statistics:** $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$: $\sim 4 \times 10^{9}$ events
  $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$: $\sim 100 \times 10^{6}$ events



Rainer Wanke, Universität Mainz, ICHEP 2006, Moscow, July 29, 2006 – p.10/16

Physics of $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$

As for $K_L\to\pi^+\pi^-\gamma$ have both Inner Brem and Direct Emission



DE can have Magnetic and Electric parts

Electric part of DE can interfere with IB

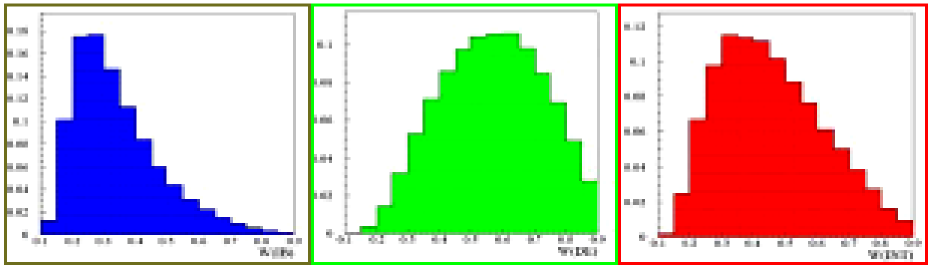
Unlike in $K_L\to\pi^+\pi^-\gamma$ IB is CP conserving, so DE is much smaller than IB

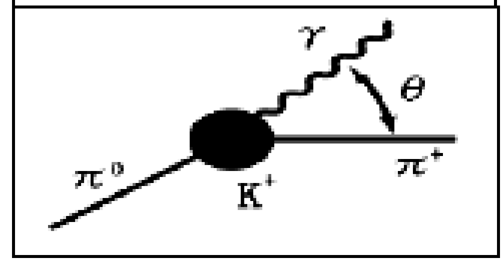
- Two Dalitz plot variables: W and T^*_π

$$W^2 = \frac{(p_K p_\gamma)(p_\pi p_\gamma)}{m_\pi^2 m_K^2}$$ (Lorentz invariant definition)

In K rest frame

$$W^2 = \frac{E_\gamma^2 (E_\pi - P_\pi \cos\theta_{\pi\gamma})}{m_K m_\pi^2}$$





- Matrix element shows separation in W^2 of components

$$\frac{d\Gamma^\pm}{dW} \simeq \underbrace{\left(\frac{d\Gamma^\pm}{dW}\right)_{IB}}_{IB} \left[1 + \underbrace{2\left(\frac{m_\pi}{m_K}\right)^2 W^2 |E| cos((\delta_1 - \delta_0) \pm \phi)}_{INT} + \underbrace{\left(\frac{m_\pi}{m_K}\right)^4 W^4 (|E|^2 + |M|^2)}_{DE}\right]$$

IB INT DE

9/18/06 Silvia Goy Lopez CD06 11

Previous experiments have not seen the INT term

NA48/2 has analysed 5 times more statistics

Two main problems that must be reduced to avoid distortions in W spectrum that might mimic DE or INT

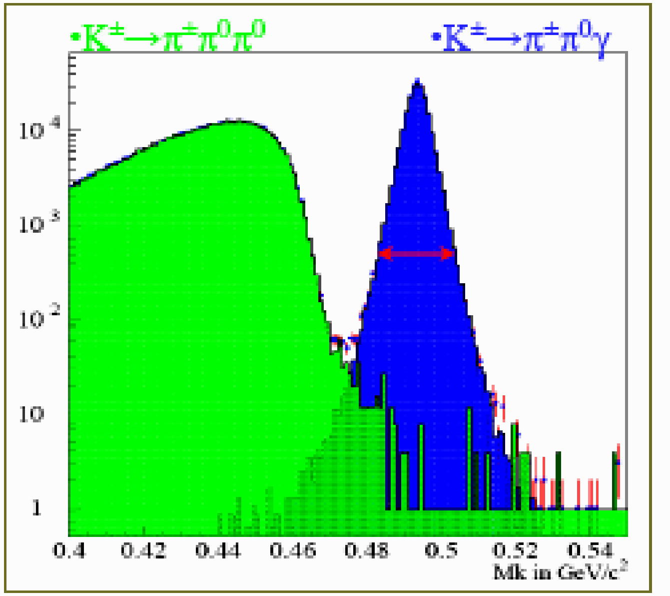
1) mis-assignment of γ's

Use best π^0 or $K^\pm$ mass and require agreement of charged and neutral vertices.

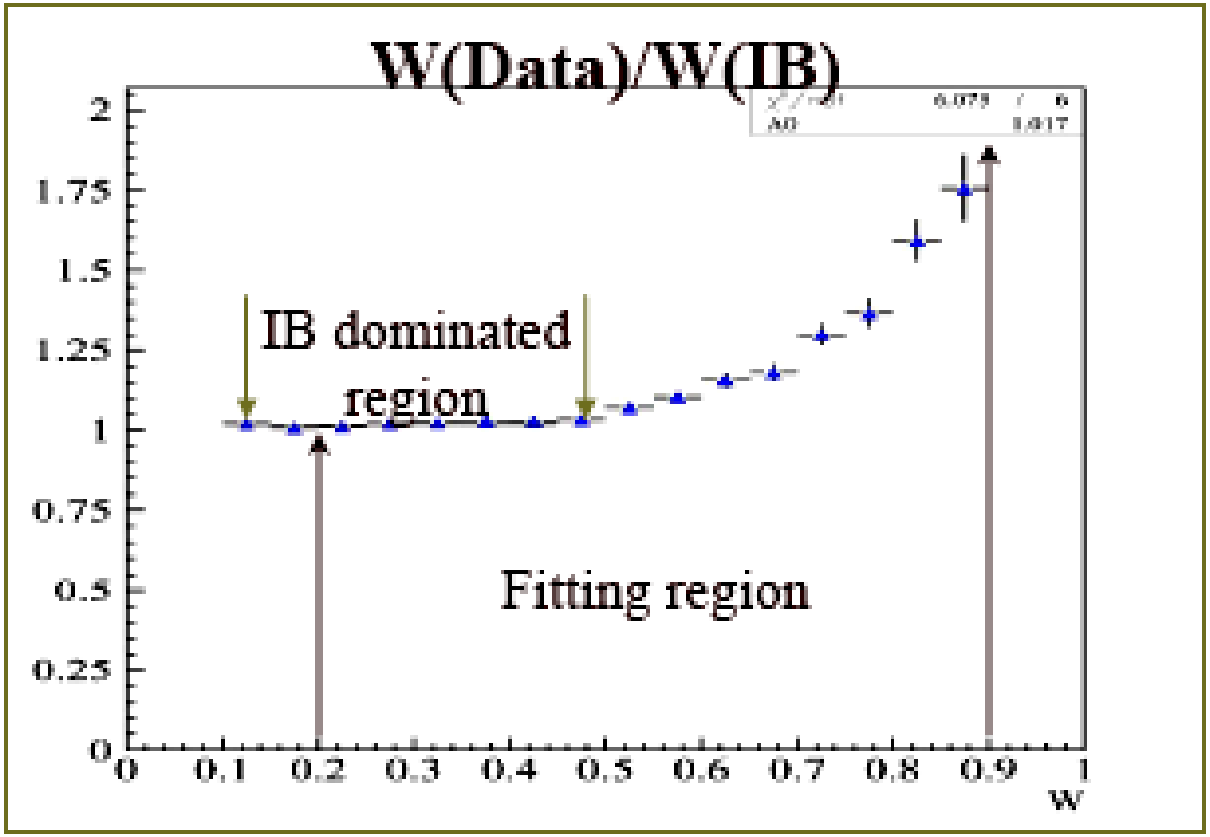
2) Backgrounds from $K^\pm \rightarrow \pi^\pm \pi^0$ and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$

Remove $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ with merged γ's by trying to split each of the γ's

Background is reduced to <1% of DE level



Results of fit to W distribution



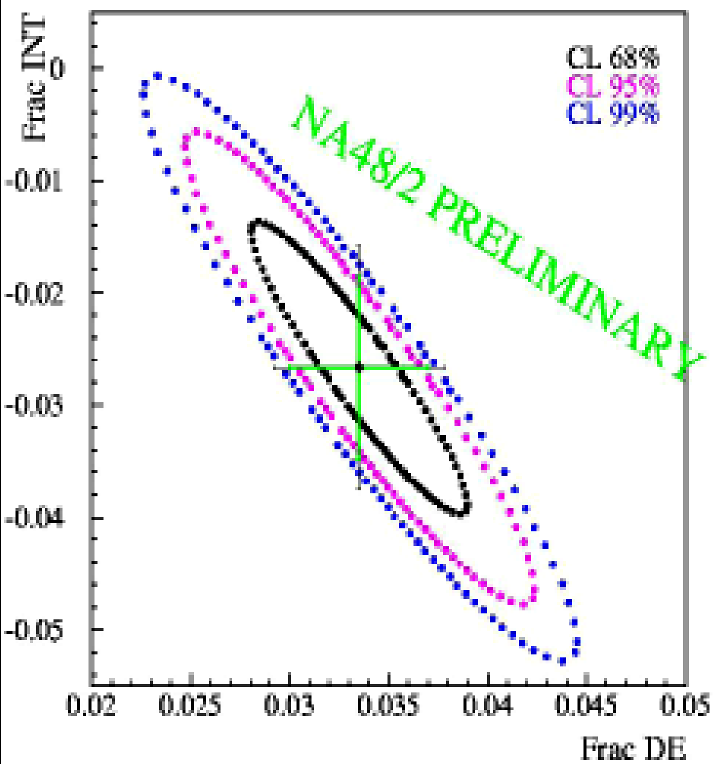
Clear evidence of DE/INT at high W

The $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay. Results

- Use extended ML for 0.2<W<0.9
- Based on 124 10^3 events
- Systematic checks:
  - Trigger efficiency dominates (trigger improved for 2004)
  - Neutral energy scale, fitting procedure, miss tagging
- First evidence of INT!

NA48/2 Preliminary: 2003 data
$0<T^*_\pi<80$ MeV

Frac(DE) = $(3.35 \pm 0.35_{stat} \pm 0.25_{syst})$ %
Frac(INT) = $(-2.67 \pm 0.81_{stat} \pm 0.73_{syst})$ %



High correlation -0.92

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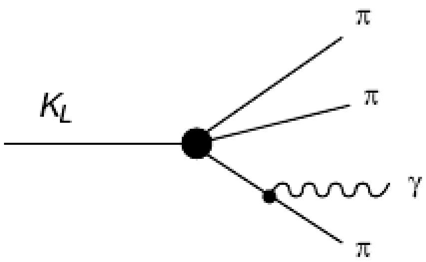
This is based on ~30% of available data

$K_L \to \pi^+\pi^-\pi^0\gamma$ and $K_L \to \pi^+\pi^-\pi^0 e^+e^-$

(Sasha Ledovskoy – University of Virginia)

internal bremsstrahlung

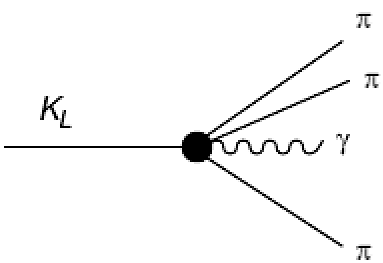


This decay is dominated by inner brem process

$$BR(E_\gamma > 10\ MeV) = (1.65 \pm 0.03) \times 10^{-4}$$

G. D'Ambrosio *et al*, Z. Phys. C **76**, 301 (1997)

direct emission



DE is estimated to be very small

$$BR\,|_{direct} = (8a_1 + a_2 - 10a_3)^2 \cdot 2 \cdot 10^{-10}$$

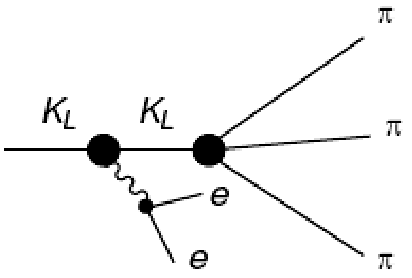
where $a_i = O(1)$ are unknown. G. Ecker *et al*, Nucl. Phys. B **413**, 321 (1994)

For $K_L \rightarrow \pi^+\pi^-\pi^0 e^+e^-$ there are no published theories

Inner Brem and DE

Same amplitude as in $K_L \to \pi^+\pi^-\pi^0\gamma$ with $\gamma^* \to e^+e^-$.

Charge radius

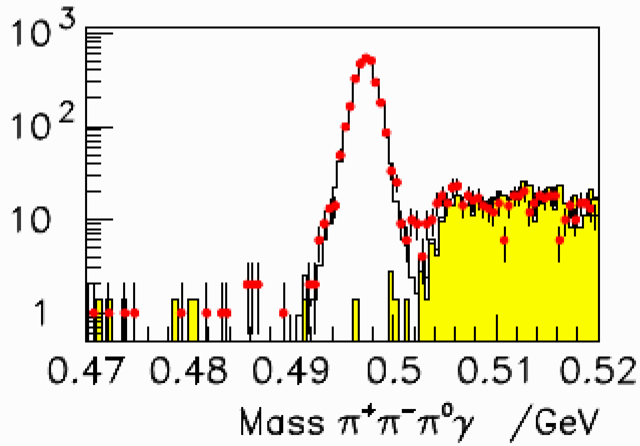


Similar to $K_L \to \pi^+\pi^- e^+ e^-$.
Is it $K_L \to K_L\gamma^*$ or $K_L \to K_S\gamma^*$?

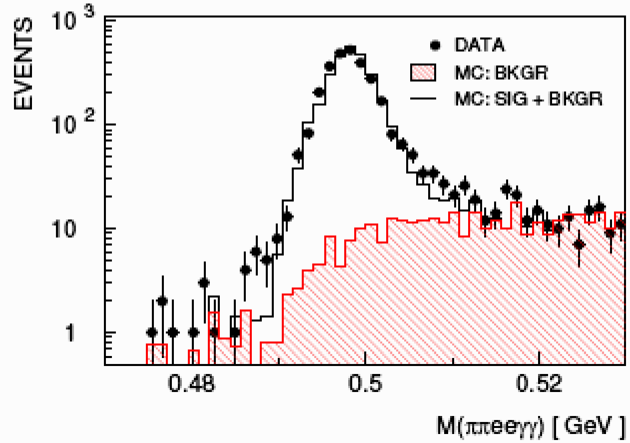
How one can measure IB, DE and CR amplitudes in $K_L \to \pi^+\pi^-\pi^0\gamma^{(*)}$ decays that have never been observed?

KTeV first observation of $K_L \to \pi^+\pi^-\pi^0\gamma$

E832: $\pi^0 \to \gamma\gamma$
2853 candidates



E799 (~40%): $\pi^0 \to e^+e^-\gamma$.
2847 candidates



KTeV Preliminary for $E_\gamma^{cm} > 10\ MeV$:

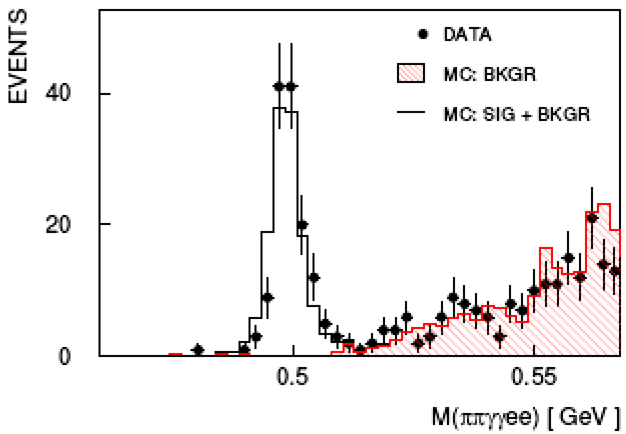
$$BR = (1.70 \pm 0.03_{stat} \pm 0.04_{syst} \pm 0.03_{norm}) \times 10^{-4}$$

Good agreement with SM calculations (ZP C76,301)

$$BR(K_L \to \pi^+\pi^-\pi^0\gamma, E_\gamma^{cm} > 10\ MeV) = (1.65 \pm 0.03) \times 10^{-4}$$

KTeV first observation of $K_L \rightarrow \pi^+\pi^-\pi^0 e^+e^-$

- E799 data,
- clean sample of 132 candidates
- estimated background level of 1.2 ± 0.9 evt
- Normalization mode is $K_L \rightarrow \pi^+\pi^-\pi^0_D$
- $\sim$40% of KTeV data anayzed



KTeV Preliminary $E_{ee} > 20$ MeV:

$$BR = (1.60 \pm 0.18_{stat}) \times 10^{-7}$$

We will try to measure Direct Emission and Charge Radius amplitudes in near future.

$K_L \rightarrow e^+e^-\gamma$

(Mike Wilking – Colorado University)

$K_L \rightarrow \mu^+\mu^-$ arises partly by a short distance coupling whose value yields a measurement of $|V_{td}|$

However it also has a long distance coupling related to $K_L \rightarrow \gamma^{(*)}\gamma^{(*)}$ which must be subtracted.

Two form factor models are usually considered.

2 parameter model of D'Ambrosio, Isidori and Portoles based on chiral perturbation theory.

Vector dominance inspired model of Bergstrom, Masso and Singer.

$$f_{BMS}(x) = \frac{1}{1 - x\frac{M_K^2}{M_\rho^2}} + \frac{C\ \alpha_{K^*}}{1 - x\frac{M_K^2}{M_{K^*}^2}}\left(\frac{4}{3} - \frac{1}{1 - x\frac{M_K^2}{M_\rho^2}} - \frac{1}{9}\frac{1}{1 - x\frac{M_K^2}{M_\omega^2}} - \frac{2}{9}\frac{1}{1 - x\frac{M_K^2}{M_\phi^2}}\right)$$

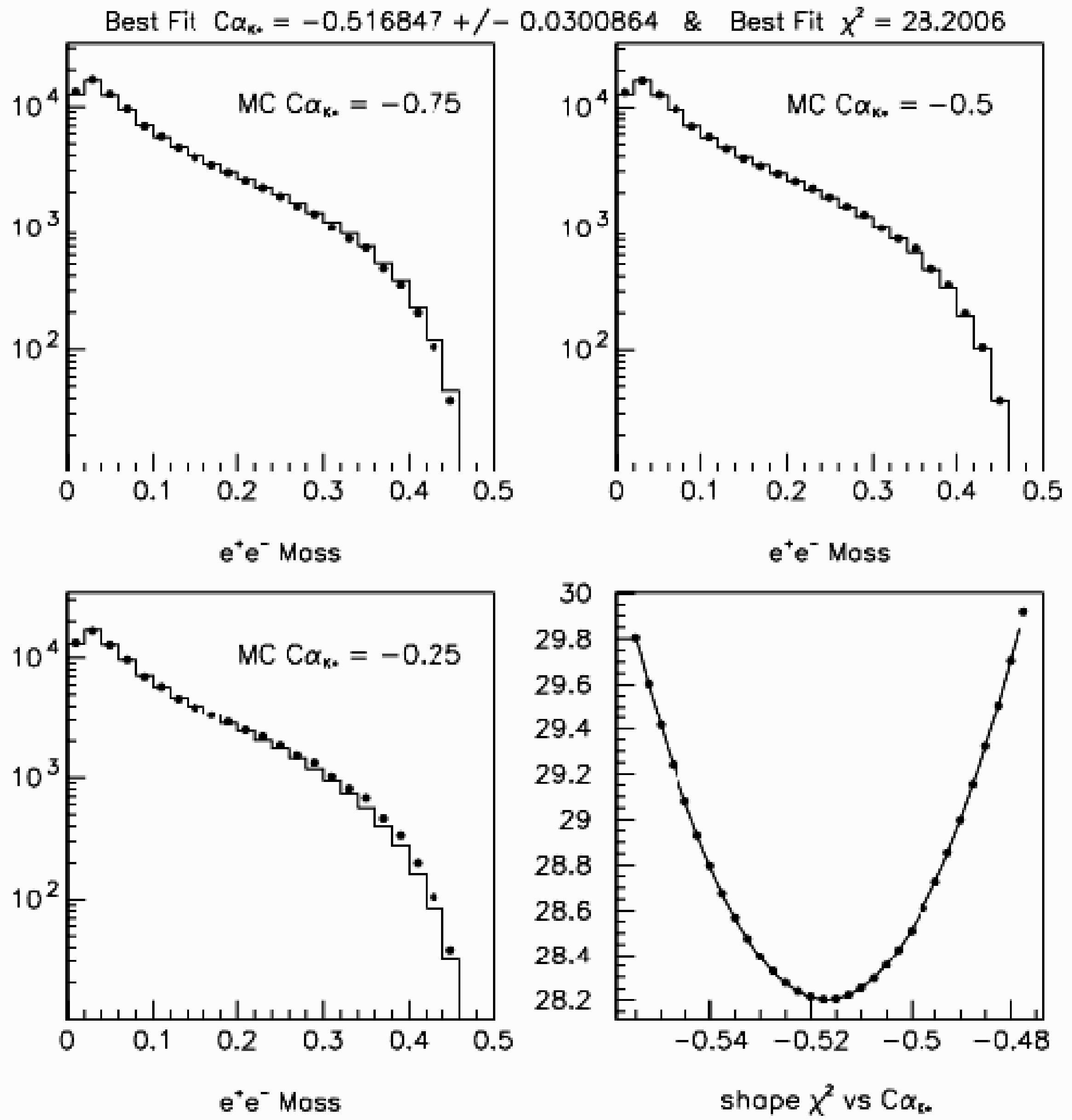
Experiments actually determine $C \cdot \alpha_K{}^*$ where C is:

$$C = (8\pi\alpha_{EM})^{1/2} G_{NL} f_K{}^*{}_{K\gamma} m_\rho{}^2 / (f_K{}^* f_\rho{}^2 A_{\gamma\gamma})$$

A number of experiments have reported values of $\alpha_K{}^*$ from various decay modes, but are inconsistent as to value of C as the parameters making up C have changed over time.

We report $C\alpha_K{}^*$ and compare it with $C\alpha_K{}^*$ from other experiments

Distribution of m_{ee} is quite sensitive to the form factor.



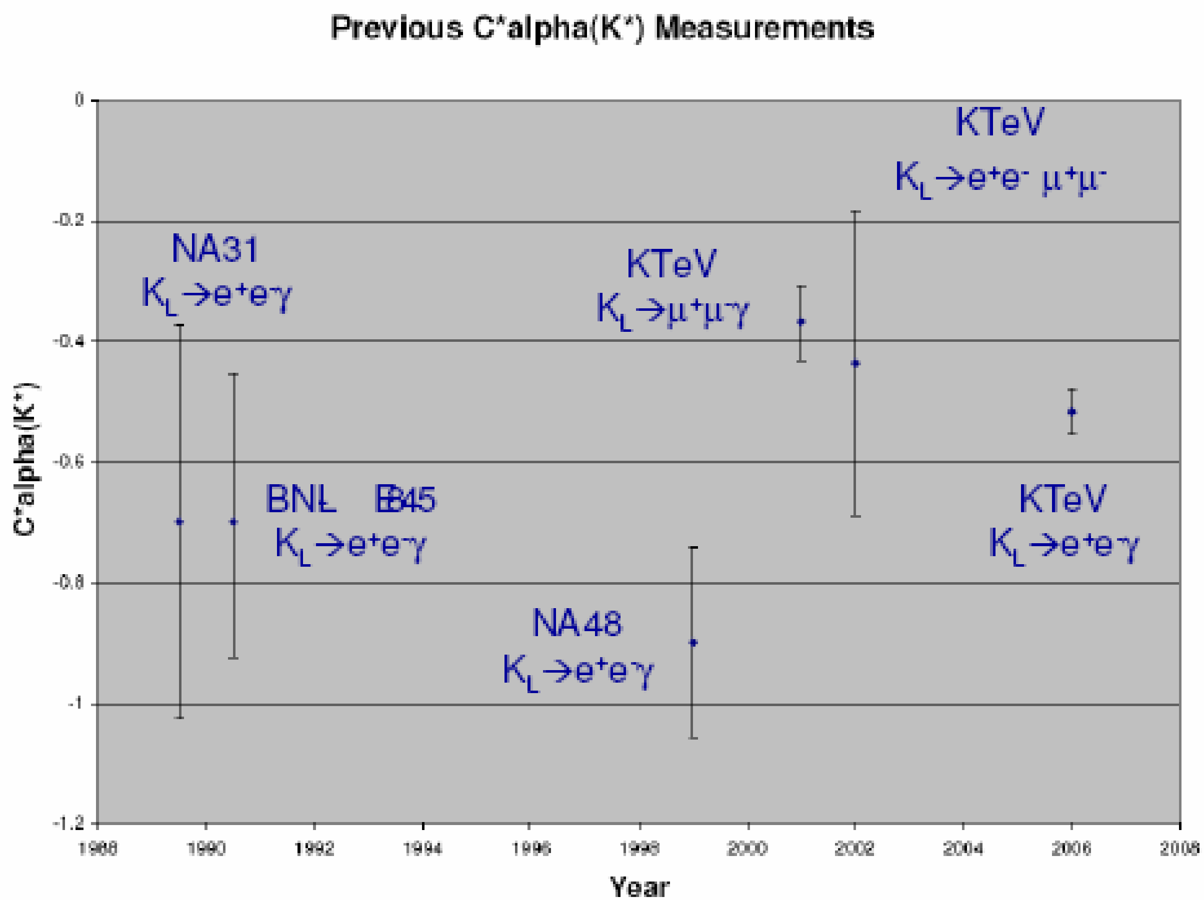
Best Fit Cα_K* = −0.516847 +/− 0.0300864 & Best Fit χ² = 28.2006
MC Cα_K* = −0.75
MC Cα_K* = −0.5
MC Cα_K* = −0.25
e⁺e⁻ Mass
e⁺e⁻ Mass
e⁺e⁻ Mass
shape χ² vs Cα_K*

Corrected preliminary KTeV $K_L \rightarrow e^+e^-\gamma$ Results

BR: $(9.25 \pm 0.03(\text{stat}) \pm 0.07(\text{syst}) \pm 0.26(\text{ext syst})) \times 10^{-6}$

$C\alpha_K^*$: $-0.517 \pm 0.030(\text{fit}) \pm 0.022(\text{syst})$

α_{DIP} : $-1.729 \pm 0.043(\text{fit}) \pm 0.028(\text{syst})$



$K_L \to \pi^{\pm} e^{\mp} \nu e^+ e^-$ (commonly called Ke3ee)

(Katsushige Kotera – Osaka University)

Because of missing ν, harder to separate out this decay

Worst backgrounds are:

$K_L \to \pi^+ \pi^- \pi^o$ ($\pi^0 \to e^+ e^- \gamma$ or $e^+ e^- e^+ e^-$)

$K_L \to \pi^{\pm} e^{\mp} \nu \pi^0$ ($\pi^0 \to e^+ e^- \gamma$)

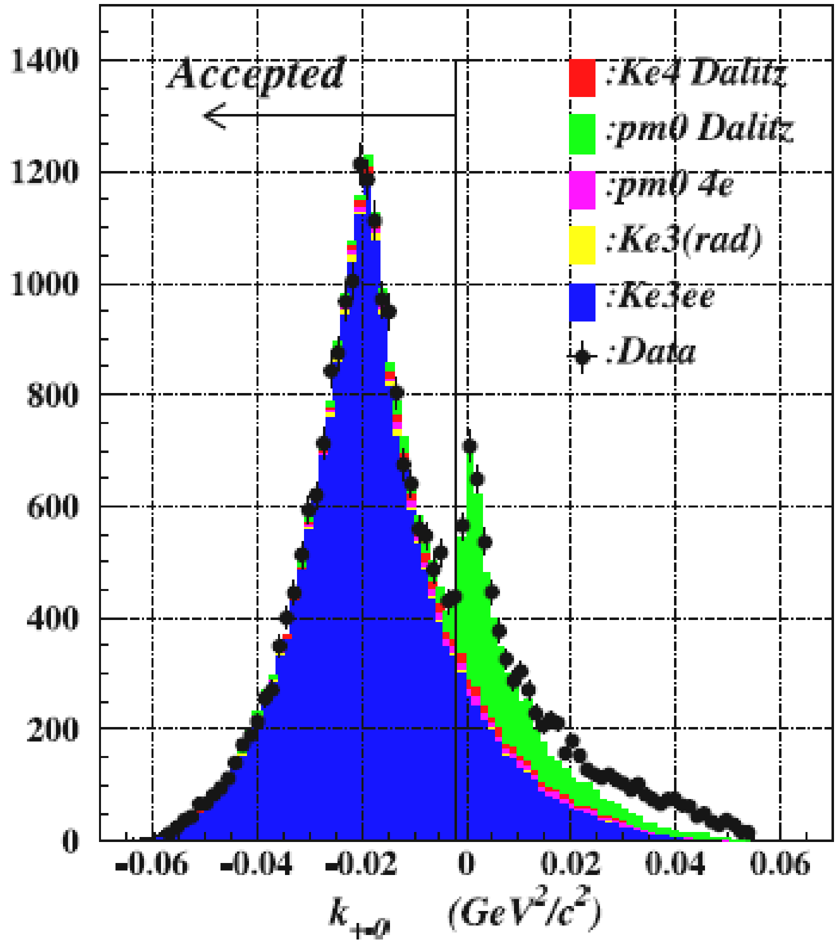
$K_L \to \pi^{\pm} e^{\mp} \nu \gamma$ (γ converts in material)

Use full π/e ID power of CsI calorimeter and the TRD's

k_{+-0} is 4 momentum squared a π^0 from a Dalitz decay would have

Calculated assuming identified e from Ke3 is actually a π

signal is mostly < 0 $\pi^+\pi^-\pi^0(\pi^0 \rightarrow e^+e^-\gamma)$ background >0



Final sample 19466 candidates with background of ~5%

(this is based on about 25% of all E799 data)

Preliminary results:

$BR[K_L \to \pi^{\pm} e^{\mp} \nu e^+ e^-; m_{e^+e^-} > 0.005\ GeV/c^2, E_{e^+e^-} > 0.03\ GeV]$

$= [1.281 \pm 0.010(stat) \pm 0.019(syst) \pm 0.035(ext\ syst)] \times 10^{-5}$

K.Tsuji (paper in preparation) has calculated in χPT the ratio:

$R = \Gamma(Ke3ee, m_{ee} > 0.005\ GeV/c^2) / \Gamma(Ke3)$

$R = 4.06 \times 10^{-5}$ at leading order

$R = 4.29 \times 10^{-5}$ at next to leading order (p^4)

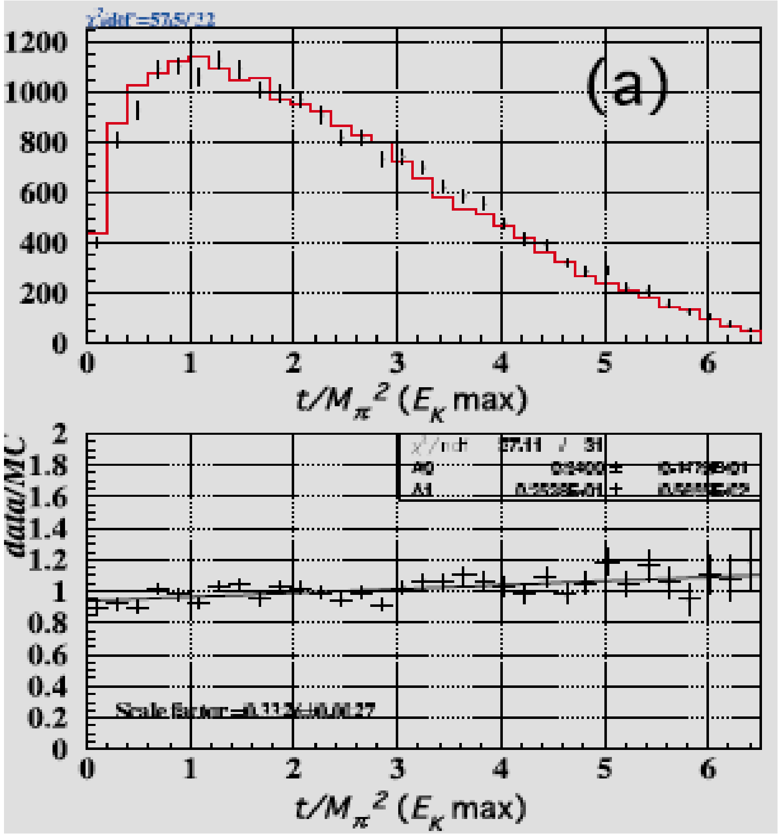
Measured BR corresponds to $R = (4.54 \pm 0.15) \times 10^{-5}$

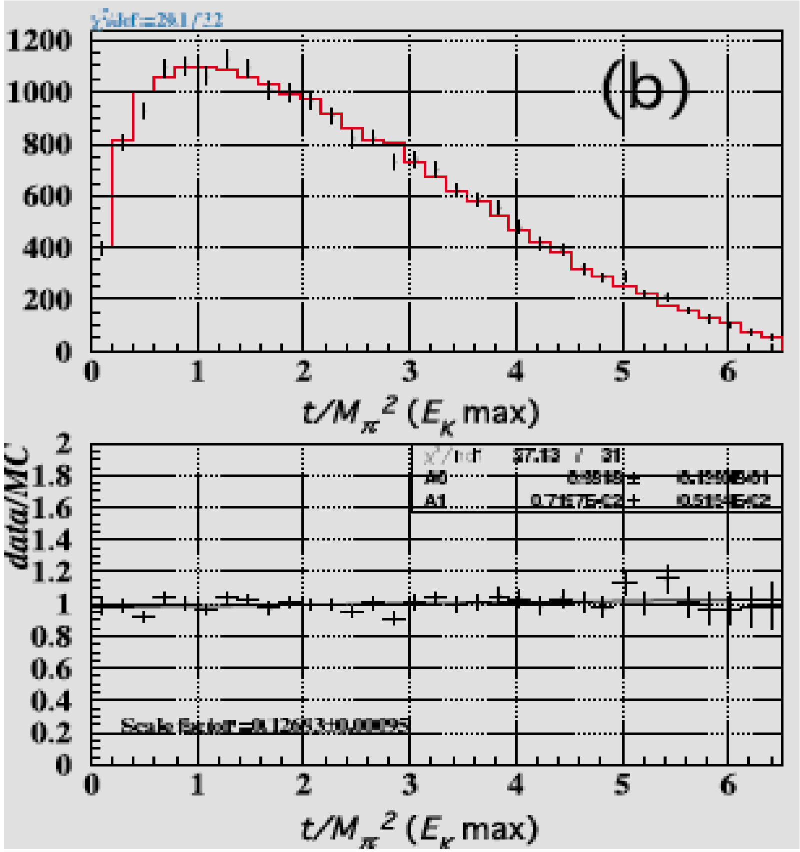
3.2σ from LO and 1.7σ from NLO

Chiral Perturbation Theory for $K_L \rightarrow \pi e \nu e e$

Leading order

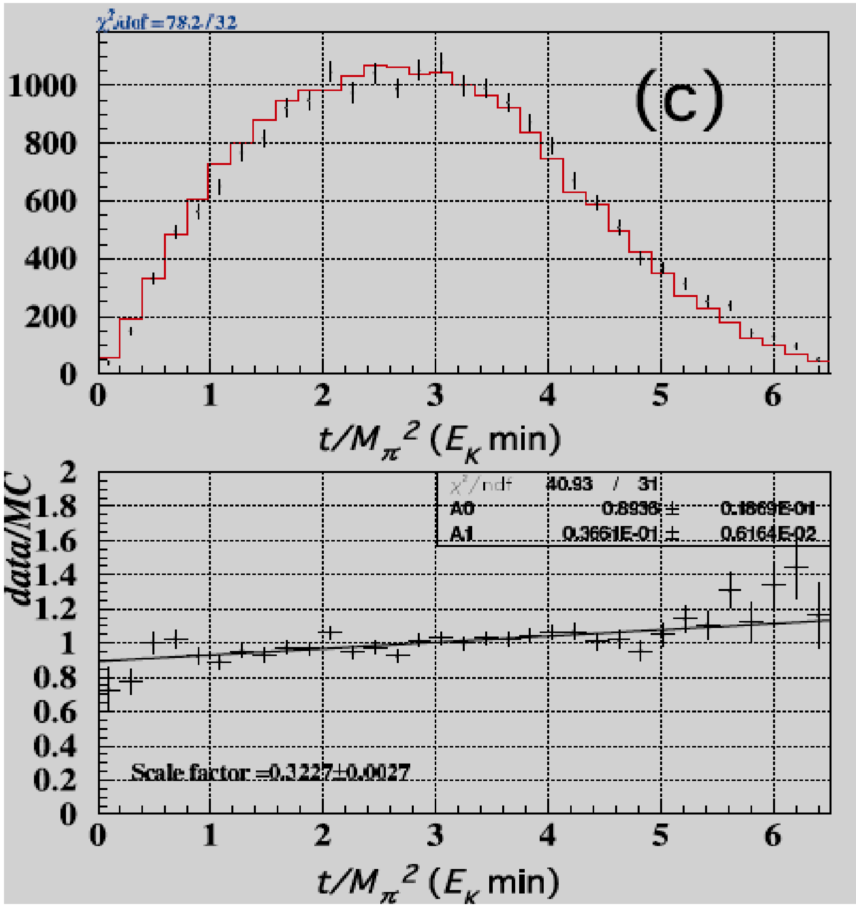
Next to leading order



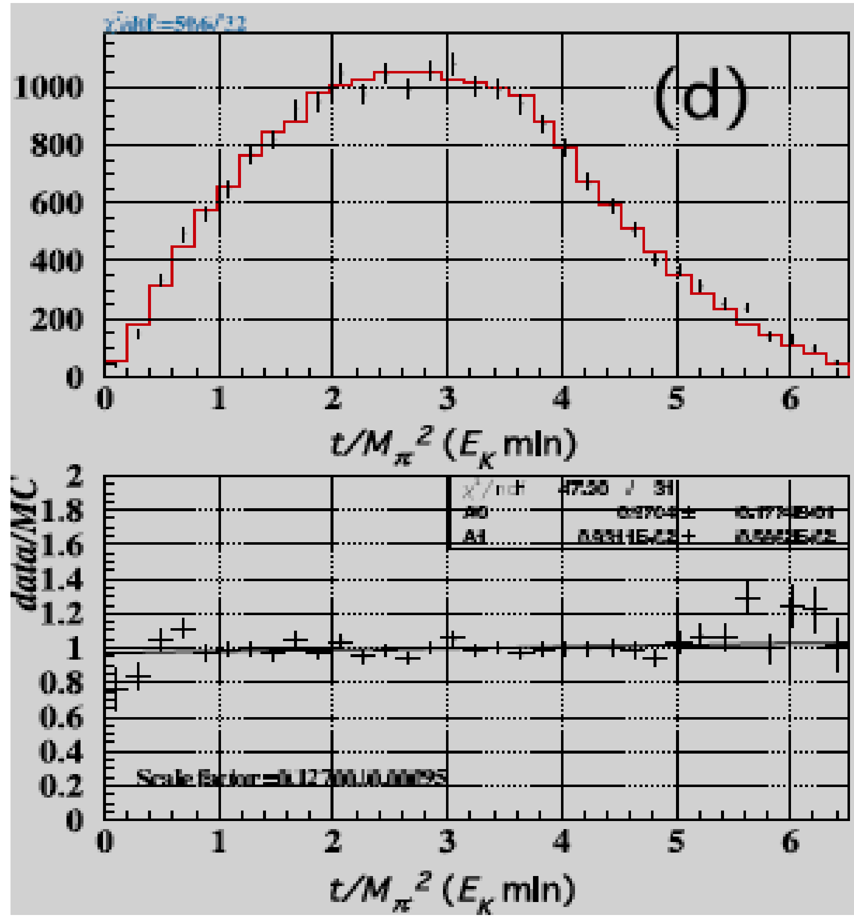


Chiral Perturbation Theory for $K_L \rightarrow \pi e \nu e e$

Leading order



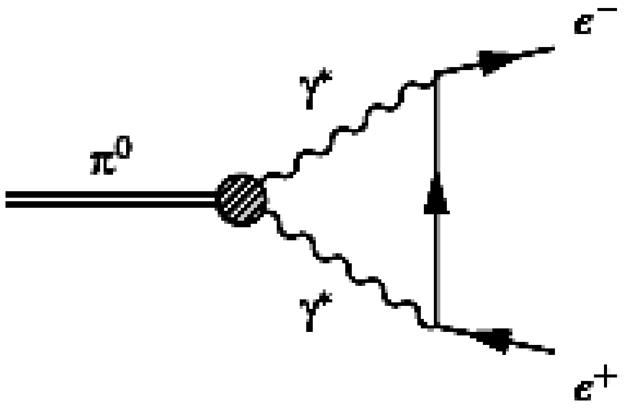
Next to leading order



$\pi^0 \rightarrow e^+e^-$

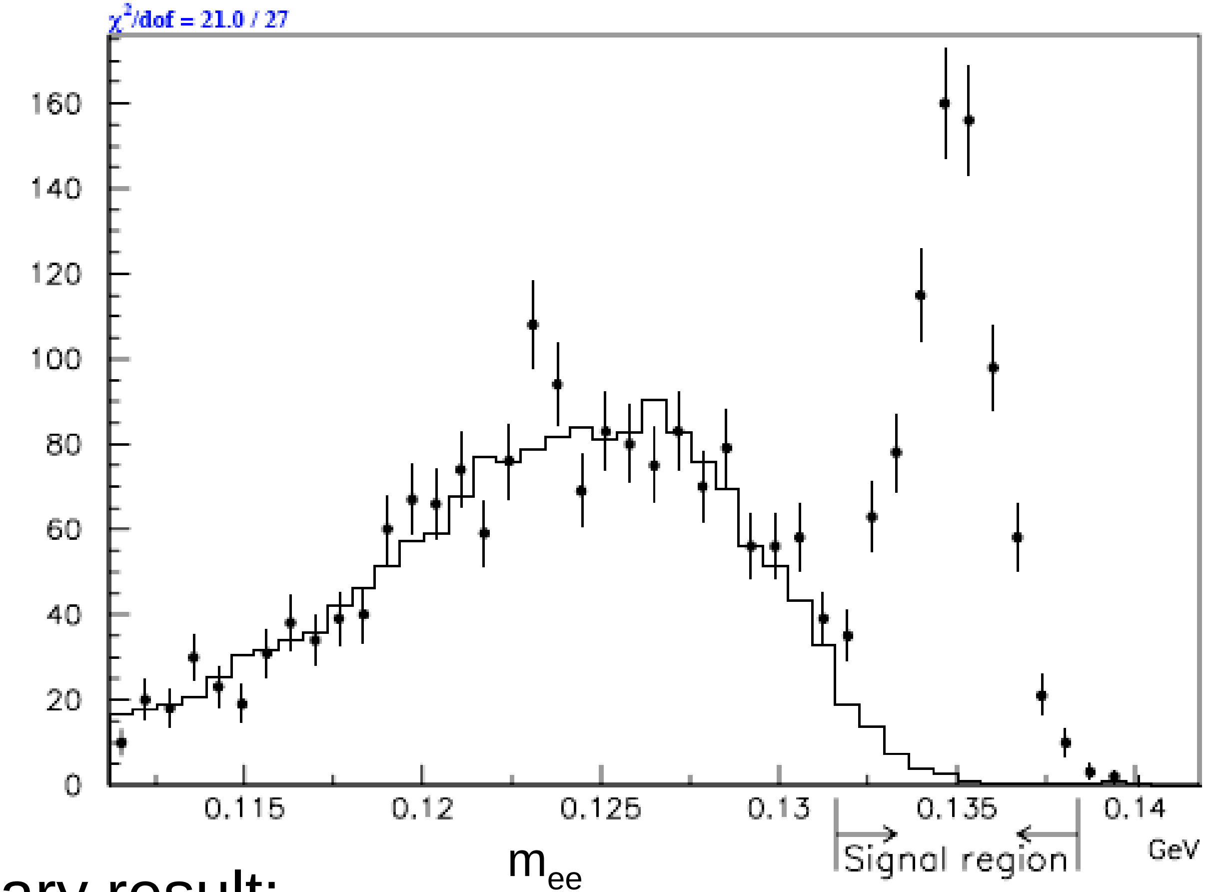
(Rune Niclasen – Colorado University)

Lowest order process
Unitarity bound
(Drell 1959)



Various Vector Dominance and
Chiral Perturbation Theory calculations
predict small enhancements above this level

π^0's are "tagged" by requiring $K_L \rightarrow \pi^0\pi^0\pi^0$

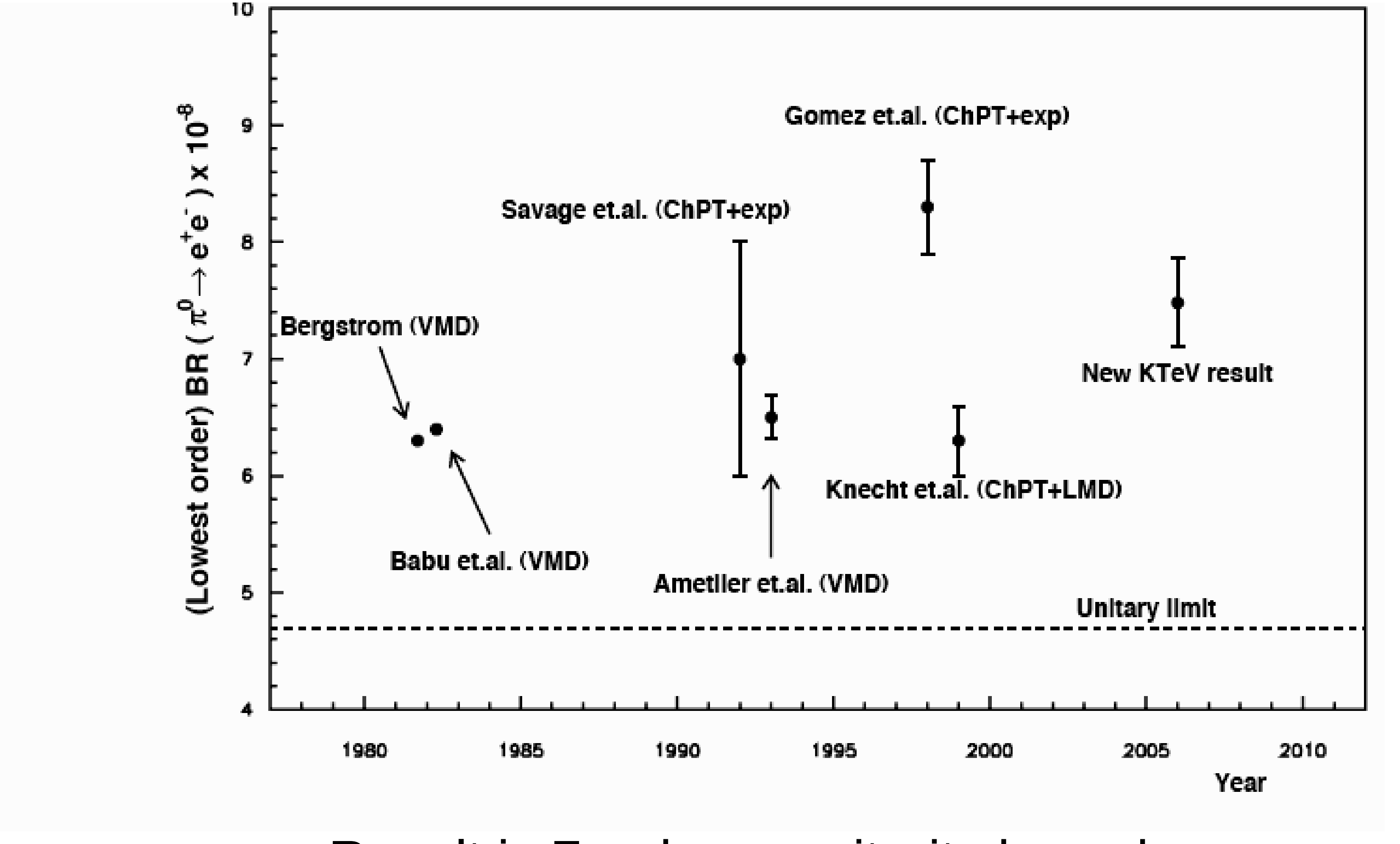


Preliminary result:

794 events with a background of 53.2 ± 9.5 events

$BR(\pi^0 \rightarrow e^+e^-, x>0.95) = (6.56 \pm 0.26 \pm 0.10(int) \pm 0.19(ext)) X 10^{-8}$

Comparison to theories



Result is 7σ above unitarity bound

Searches for Lepton Flavor Violating Modes

$K_L \rightarrow \pi^0 \mu^\pm e^\mp$ $K_L \rightarrow \pi^0 \pi^0 \mu^\pm e^\mp$ $\pi^0 \rightarrow \mu^\pm e^\mp$

Marj Corcoran – Rice University

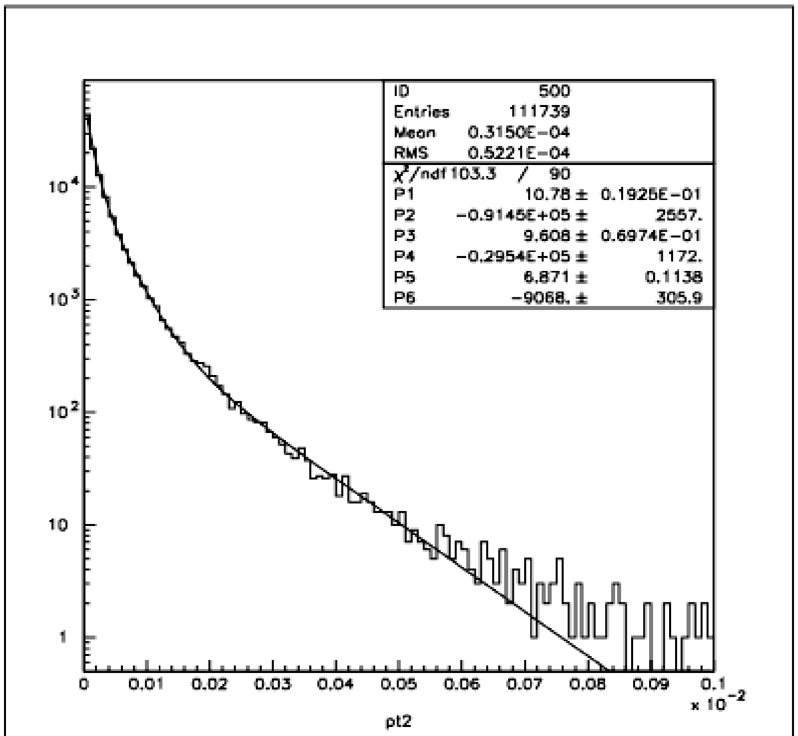
Final combined analysis of entire KTeV dataset in progress.

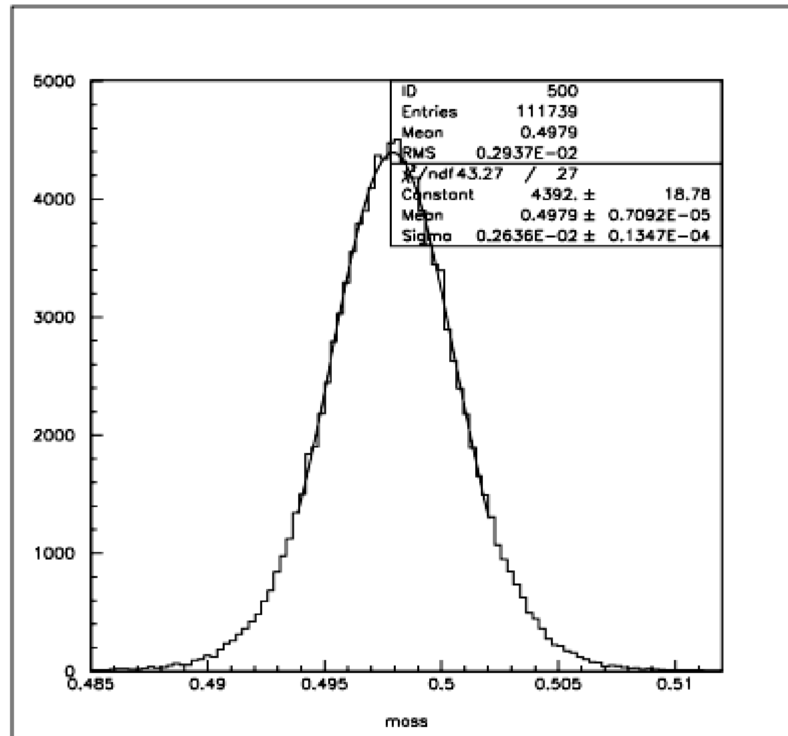
No new result on $K_L \rightarrow \pi^0 \mu^\pm e^\mp$

Very new result – Box opened last week – for $K_L \rightarrow \pi^0 \pi^0 \mu^\pm e^\mp$ and $\pi^0 \rightarrow \mu^\pm e^\mp$

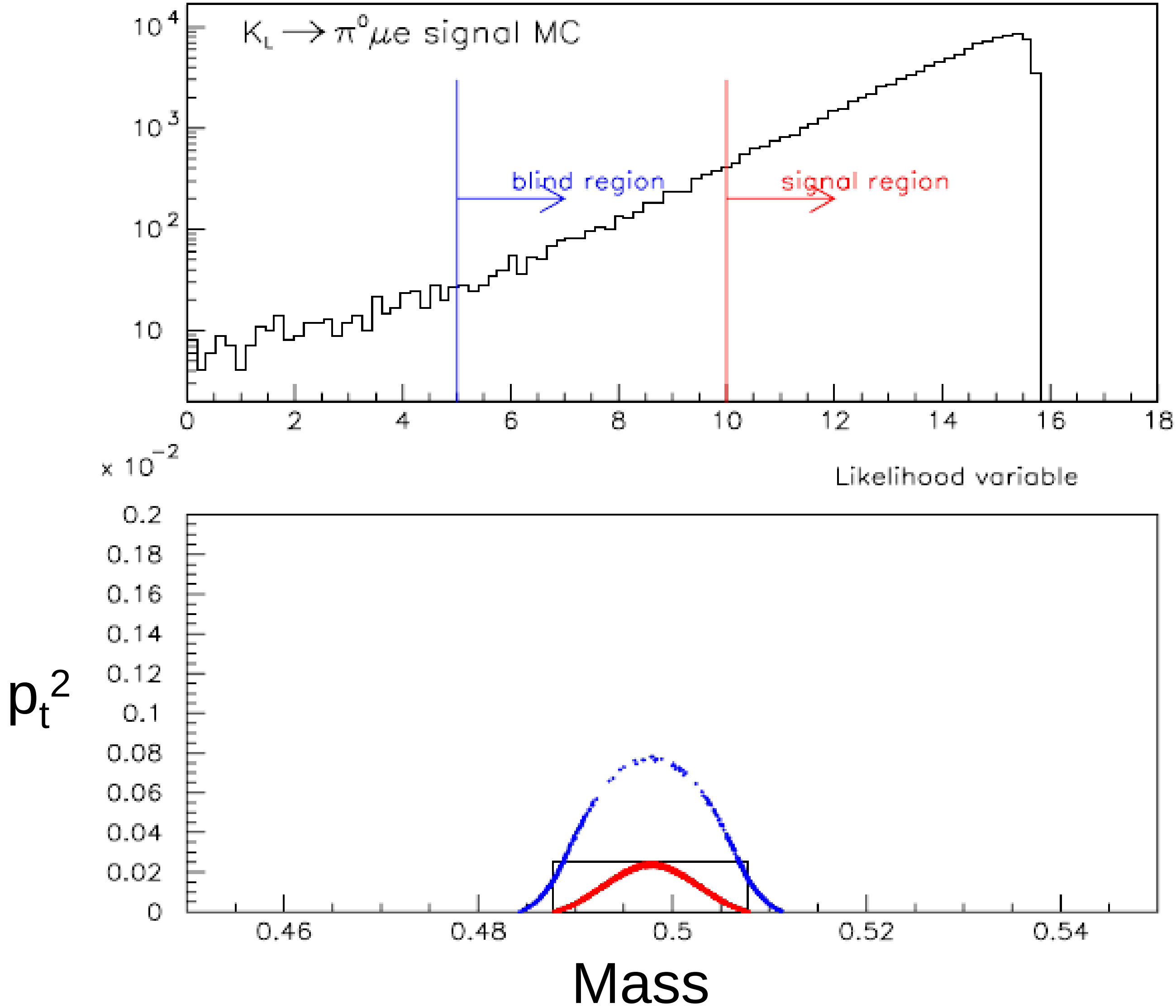
After cuts to remove background final selection is usually made on $m_{\pi\pi\mu e}$ and p_t^2 with respect to K_L flight direction, defining a “box”.

Instead we define a probability distribution function (pdf) that m and p_t^2 have appropriate values.





Defining the search region



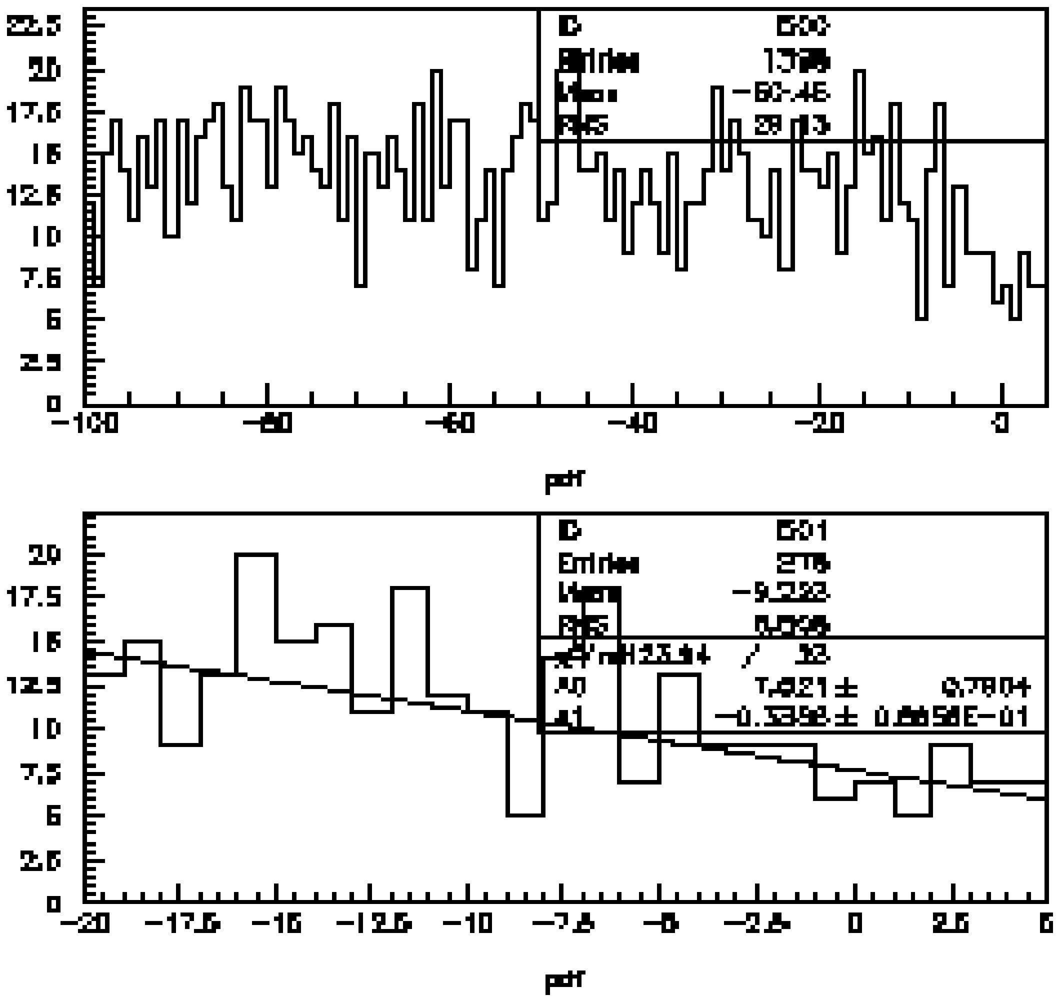
Backgrounds appear to be from a little bit of everything

Impossible to generate enough Monte Carlo to simulate.

Probably cannot trust Monte Carlo at 10^{-10} level

Instead estimate background from data, but not enough events left after final cuts to extrapolate to signal region

Determine background from data by fitting pdf for data with relaxed cuts



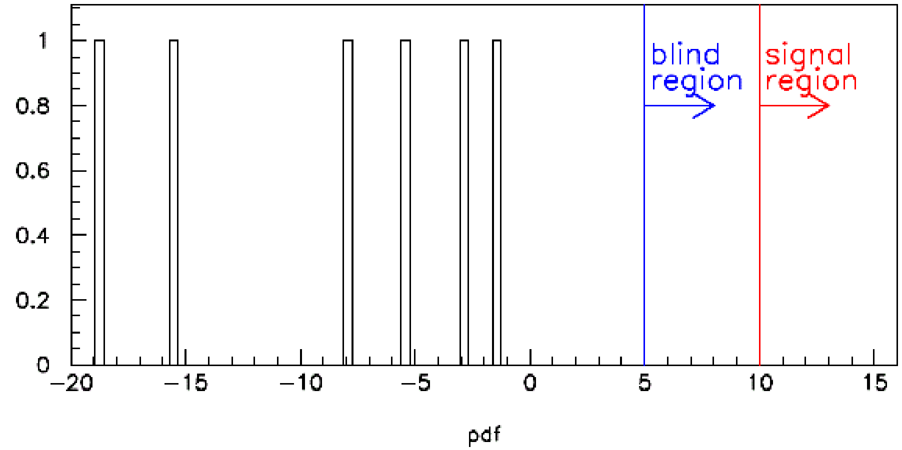
Signal region

Is pdf>10

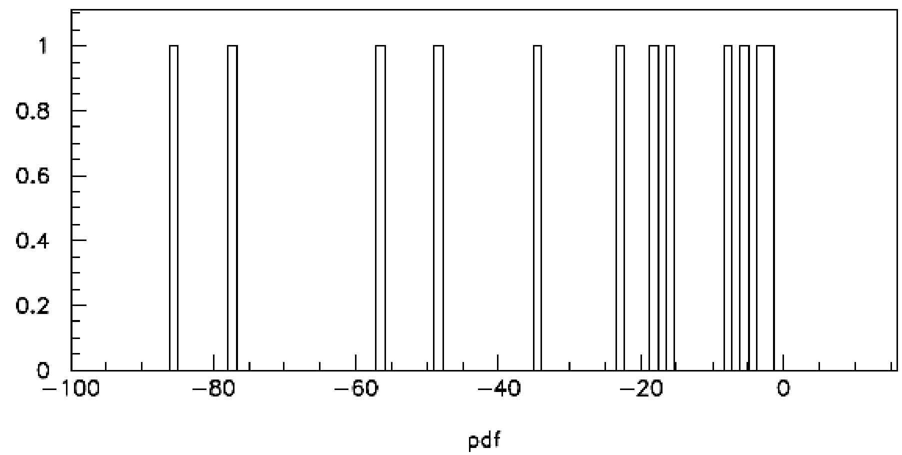
Expected backgrounds:

$K_L \to \pi^0\pi^0\mu^\pm e^\mp$ 0.44 $\pm$ 0.12 events

$\pi^0 \to \mu^\pm e^\mp$ 0.03 $\pm$0.02 events



Box opened, no events seen in either signal or blind region



Preliminary result using Feldman-Cousins method

90% confidence level upper limits

$BR(K_L \rightarrow \pi^0\pi^0\mu^{\pm}e^{\mp}) < 1.58 \times 10^{-10}$

$BR(\pi^0 \rightarrow \mu^{\pm}e^{\mp}) < 3.63 \times 10^{-10}$

Summary

Recent very sensitive results from KTeV and NA48 on:

$K_L \to \pi^+\pi^-\gamma$

$K^\pm \to \pi^\pm\pi^0\gamma$

$K_L \to \pi^+\pi^-\pi^0\gamma^{(*)}$

$K_L \to e^+e^-\gamma$

$K_L \to \pi^\pm e^\mp \nu e^+e^-$

$\pi^0 \to e^+e^-$

lepton flavor violating modes